# On the structure of the mean flow in the Blanes Canyon area (NW Mediterranean) during summer

Submarine canyon
Western Mediterranean
Water masses
Circulation
Remote sensing

Canyon sous-marin
Méditerranée Occidentale
Masses d'eau
Circulation
Télédétection

**Pilar ROJAS [a], Marc Antoni GARCÍA [a], Joaquim SOSPEDRA [a], Julia FIGA [a], Joan PUIG DE FÀBREGAS [a], Oswaldo LÓPEZ [a], Manuel ESPINO [a], Victor ORTIZ [a], Agustin SANCHEZ-ARCILLA [a], Mario MANRÍQUEZ [b] and Bernardo SHIRASAGO [b]**

[a] Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya (UPC), c/Gran Capitán s/n, mòdul D1, 08034 Barcelona, Spain.

[b] Institut de Ciències del Mar, Passeig Joan de Borbó s/n, 08039 Barcelona, Spain.

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ABSTRACT

The MECA 93 oceanographic cruise was carried out in June 1993. The main purpose of the experiment was to understand the action of the main driving mechanisms responsible for the flow variability in the Blanes canyon area (NW Mediterranean) during summer.
A domain of about 4000 km$^2$ including the canyon was covered by R/V *Hespérides* between 17 and 22 June 1993. CTD sampling was performed with characteristic spacing between adjacent stations of 7 to 15 km.
The water masses distribution observed during the cruise corresponds to a classical, well-established summer stratification, with typical surface temperatures above 22 °C. The thermocline was located at a 40 m depth. The TS diagrams reveal water exchanges across the shelf edge. The surface distributions of temperature and salinity display patches of cool and low-salinity water on the slope.
The flow distribution which emerges from ADCP measurements performed throughout the cruise does not match the fully topographically-steered circulation pattern expected on the basis of previous model results. The surface currents on the shelf are northeastwards, *i.e.* opposite to the southwestward general circulation on the continental slope. This result is in agreement both with the surface circulation picture evidenced by a contemporary SAR scene acquired by ERS-1 and with the trajectories of the LCD drifters launched north of the canyon at the outset of the cruise. ADCP measurements at depths below 50 m suggest that the prevailing flow pattern on the shelf was reversed below the thermocline. We assume that the inflow of relatively cold and low-salinity water advected from the Gulf of Lions was responsible for an inversion of the horizontal pressure gradient which forced the surface current reversal on the shelf.

RÉSUMÉ

Structure du flux moyen dans le canyon de Blanes (Méditerranée nord-occidentale) en été.

La croisière océanographique MECA 93 a été réalisée en juin 1993. L'objectif principal de l'expérience était de comprendre l'action des principaux mécanismes responsables de la variabilité des courants dans la zone du canyon de Blanes (Méditerranée nord-occidentale) pendant l'été.
Une région d'environ 4000 km$^2$ autour du canyon de Blanes a été échantillonnée par le bateau de recherche *Hespérides* entre le 17 et le 22 Juin. Des sondages CTD ont été effectués dans des stations adjacentes distantes de 7 à 15 km.

La répartition des masses d'eau observée pendant la croisière MECA 93 correspond à une stratification normale d'été, avec des températures de surface typiques supérieures à 22 °C. La thermocline était située à 40 m de profondeur. Les diagrammes TS révèlent des échanges d'eau du talus à travers la marge continentale. Les distributions de la température et de la salinité de surface montrent certaines masses d'eau froide et peu salée sur le talus.
La structure de l'écoulement d'après les mesures ADCP réalisées pendant la campagne ne correspond pas au schéma d'une circulation gouvernée par la topographie, comme on aurait pu l'espérer d'après les résultats de la modélisation préalable. Les courants superficiels sur la plateforme sont de direction NE, c'est-à-dire, à l'inverse de la circulation générale, de direction SO sur le talus continental. Ce résultat est en accord à la fois avec l'image de la circulation de surface mise en évidence par des images SAR contemporaines de l'ERS-1, et avec les trajectoires des flotteurs LCD équipés et lancés au nord du canyon au début de la croisière. Les mesures ADCP réalisées à plus de 50 m de profondeur suggèrent que la structure des courants dominants sur le plateau est inversée au-dessous de la thermocline. Nous supposons que l'entrée d'eau relativement froide et peu salée advectée du Golfe du Lion est responsable du renversement du gradient de pression horizontal qui a forcé une inversion du courant superficiel sur le plateau.

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## INTRODUCTION

Submarine canyons are prominent bathymetric features which are responsible for spatial variations of the circulation on the continental shelf and slope domains. A few papers have addressed the effects of the submarine canyons on the shelf circulation off the NE Spanish coast. Masó *et al.* (1990) pointed out that these canyons act as barriers that deflect the general southwestward circulation in the sense that the flow is shelfward upstream of each canyon and offshore on the downstream side. La Violette *et al.* (1990) reported remote sensing observations of offshore-flowing filaments downstream of the Foix canyon. Masó and Tintoré (1991) observed a small positive vorticity area at the Palamós canyon and also a larger anticyclonic circulation area over the shelf south of the canyon. A similar pattern was found in the Creus canyon region.

In all these papers, the observed flow structures are explained in terms of potential vorticity constraint of a barotropic flow assuming no friction. Ertel's theorem applied to the Liguro-Provençal-Catalan (or Northern) Current in the Western Mediterranean predicts that it should veer towards shallow depths at all levels upstream of a canyon. The resultant negative relative vorticity would be offset by the decrease in depth. Over the canyon, the depth increase would induce positive potential vorticity, which would result in offshore flow at the downstream side. None of the authors discussed the effects of the water stratification on the observed current patterns.

A field experiment was conducted in the Blanes canyon in June 1993 to investigate the flow structure in this area during summer (Fig. 1). The experiment was a part of a two-year project funded by the Spanish Interministerial Commission of Science and Technology whose main objective was a better understanding of the dynamics of mesoscale distortions of the circulation on the Catalan continental shelf.

## EXPERIMENTAL DESIGN

The MECA 93 experiment was carried out between 17 and 22 June 1993 on board R/V *Hespérides*. 47 stations with characteristic spacing of 7 to 15 km were occupied in a 4000 km$^2$ area including the Blanes canyon (Fig. 2). Routine operations at the cruise stations comprised CTD casts performed with an EGG MkV unit, water sampling with GO Rosette and ADCP measurements obtained by means of a RDI 150 kHz vessel-mounted narrowband system. While steaming between sampling stations, additional

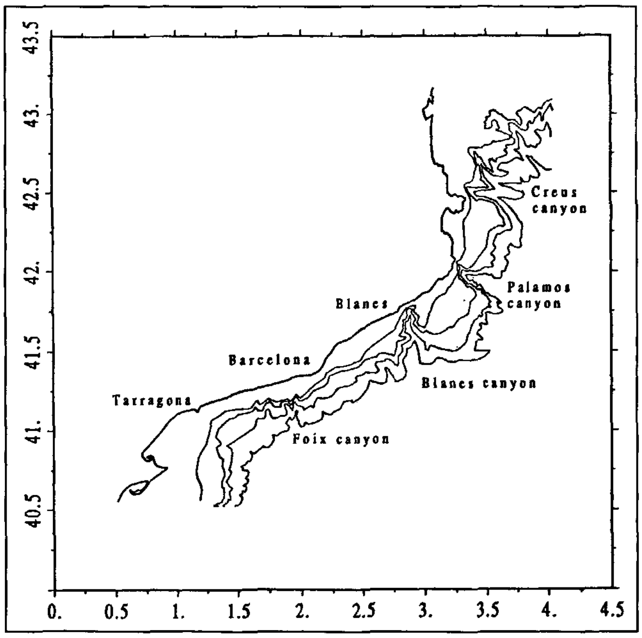



Figure 1

*Location of the Blanes canyon at the Catalan continental shelf break. The 100, 200, 400 and 1000 m isobaths are depicted.*

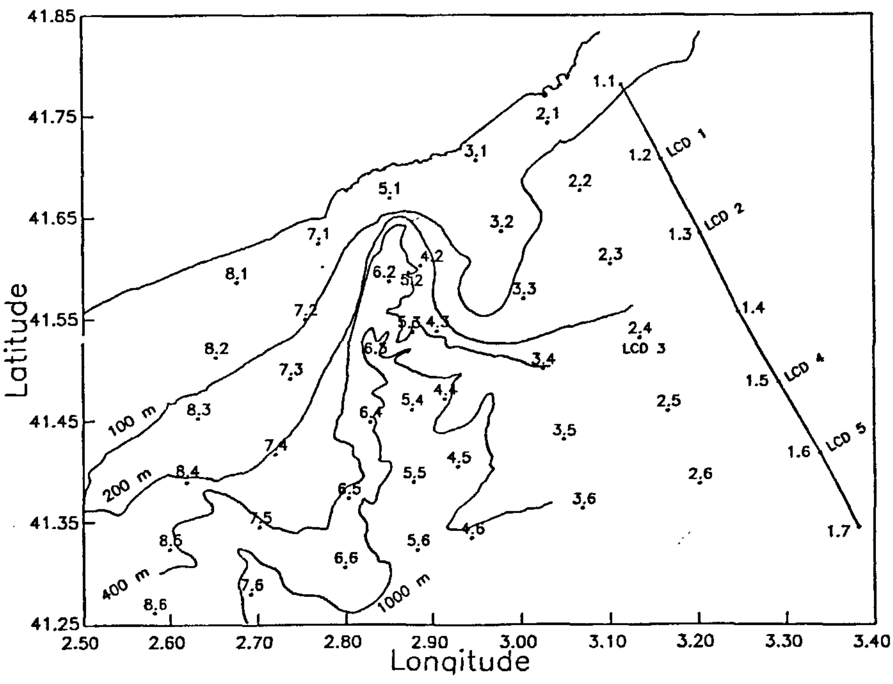


Figure 2

*MECA 93 cruise. Station map and LCD release locations.*

ADCP records and surface TS data acquired with a SBE 21 thermosalinograph were obtained. For data post-processing tasks, a VAX ALFA AXP 7000 mainframe and a personal computer were used.

Also as a part of the experiment, five Lagrangian drifters of the LCD type were launched at selected locations north of the canyon shortly after the beginning of the cruise. The drifters were equipped with a 10-metre drogue whose centre line was at the 20 m depth layer. They were subsequently tracked via Service Argos until the end of August.

In addition, the data acquisition plan envisaged a request for contemporary SAR.PRI imagery from ESA, and this was successfully acquired by ERS-1 on 17 June. Processing of the SAR scene included elimination of the speckle noise by means of a Wiener adaptative filter and image geometrical correction. Wind conditions during the image acquisition were adequately mild so that surface oceanographic features could be identified through visual inspection. Finally, a set of ten NOAA/AVHRR images covering the period 18 June to 14 August was ordered through INTA/NPOC from ESA. After land masking and cloud removal, SST distributions were computed by means of a locally fitted triple-window algorithm (Robinson, 1985). The SAR and NOAA images were processed with PC-based ERDAS modules and a number of utilities supported by a Sun Microsystems workstation.

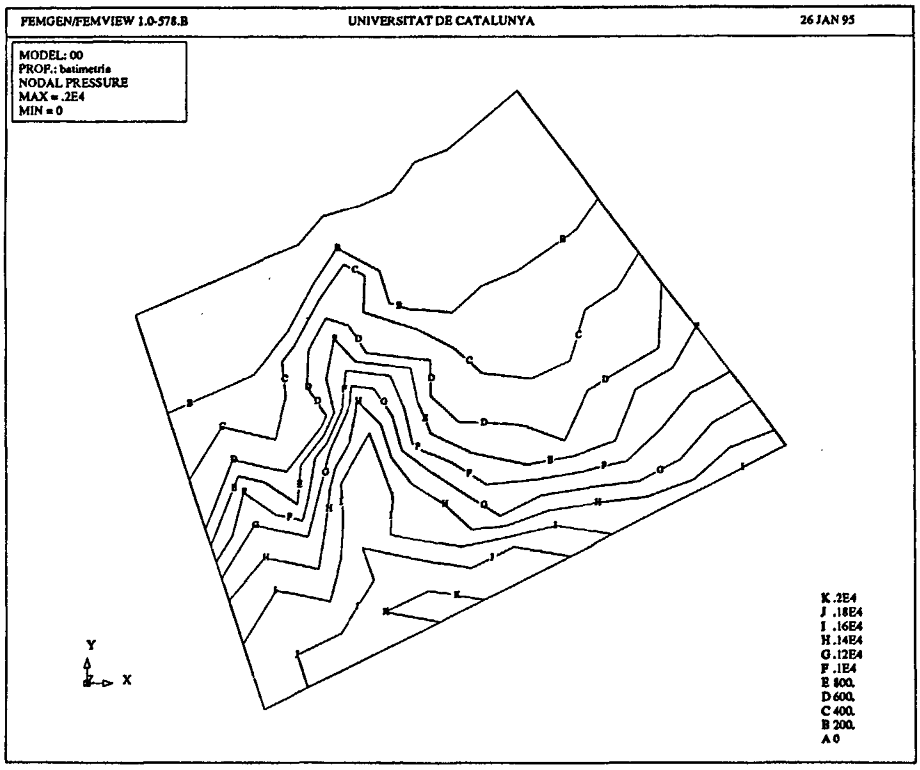
## WORKING HYPOTHESIS

A working hypothesis for the overall current structure in the Blanes canyon area was built up with the aid of a finite element model of the steady-state shallow-water equations developed at the Laboratori d'Enginyeria Marítima of UPC. A detailed description of the model can be found elsewhere (Espino, 1994).

The study area was discretized with the rough computational grid shown in Figure 3. The simulation was performed assuming homogeneous density and no wind conditions, and only the vertically-averaged flow field was solved. Bilinear polynomials were used as shape functions for the velocity, whereas the pressure was interpolated with piecewise constant functions. As regards the boundary conditions, a uniformly increasing current velocity distribution was specified on the northeastern boundary. Constant Dirichlet conditions were considered for the coastal and outer boundaries of the computational domain, whereas a free-outflow Neumann condition was imposed on the southwestern boundary. As regards the free model parameters, constant horizontal eddy viscosity ($K_H$ =500 $m^2/s$) and bottom friction coefficients ($\gamma_b$= 1 to 100 $Kg/m^3s$) were selected within the range of values normally used in the oceanographic literature.

Figures 4a and 4b show some representative computed current velocity fields. The solution shown in Figure 4a, which was obtained with a low bottom friction coefficient, exhibits a character which agrees with that expected from conventional potential vorticity conservation arguments, namely a negative vorticity region upstream of the canyon, a cyclonic circulation area within the canyon itself and again a flow with negative vorticity downstream. These features are independent of the flow on the outer slope. The extrusion of water filaments across the shelf break at the downstream side of the canyon is somewhat obscured by the condition imposed on the outer boundary.

The model results presented in Figure 4b were obtained with a higher (by two orders of magnitude) bottom friction coefficient. They suggest that the bottom friction may be responsible for an offshore shift of the current south of the canyon. Further numerical investigation is in progress to obtain a better understanding of this process.

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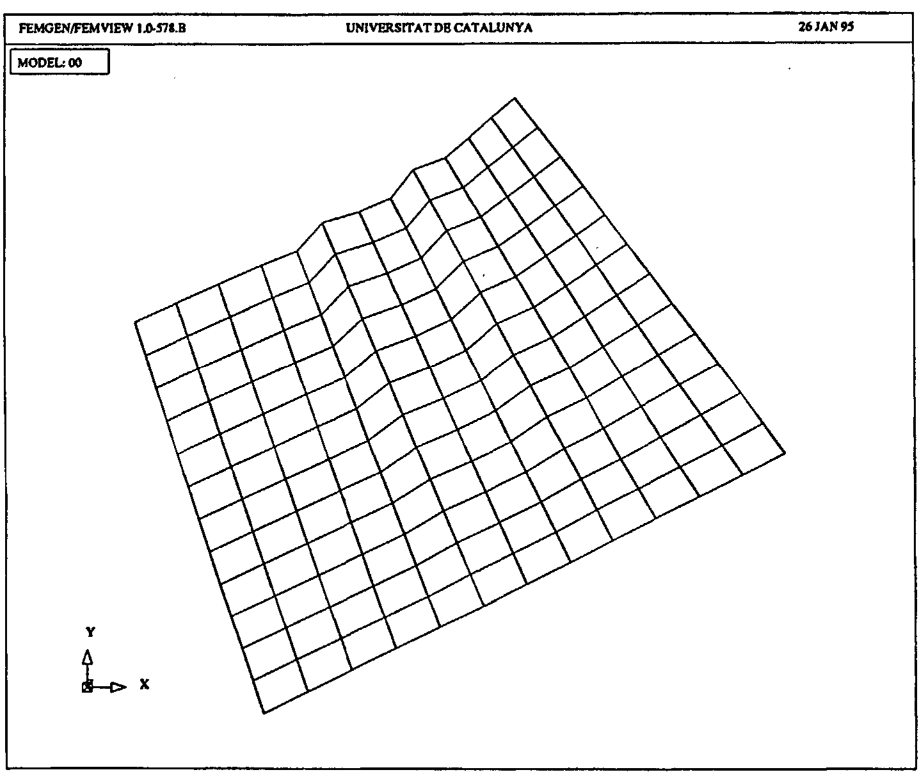
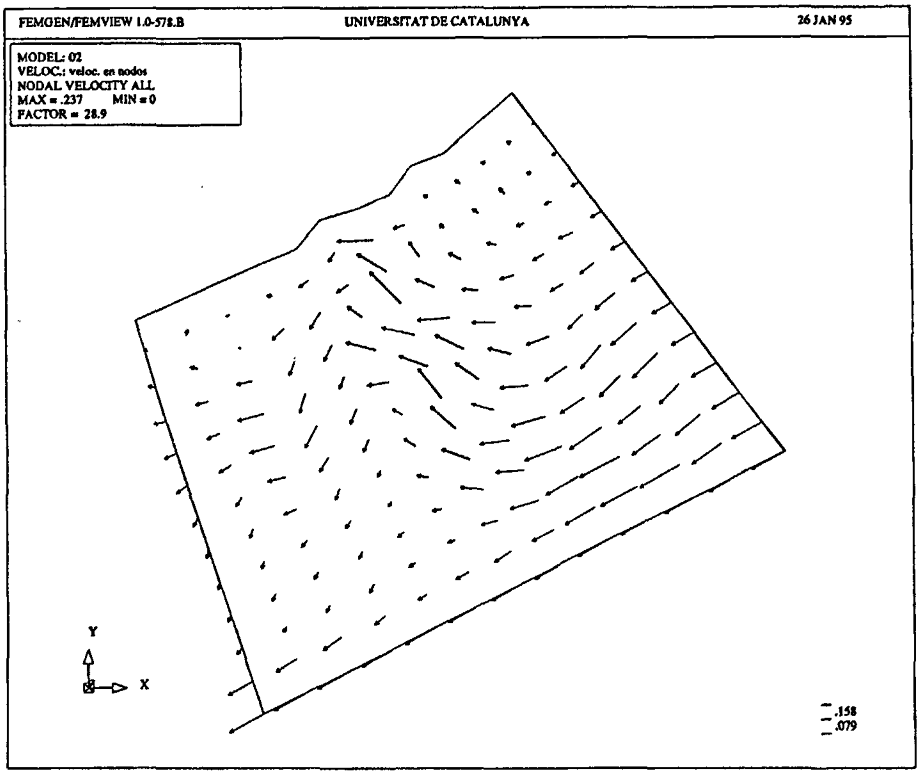



b

Figure 3

*Numerical simulation of the flow in the Blanes canyon area. a) Model bathymetry. b) Computational grid.*

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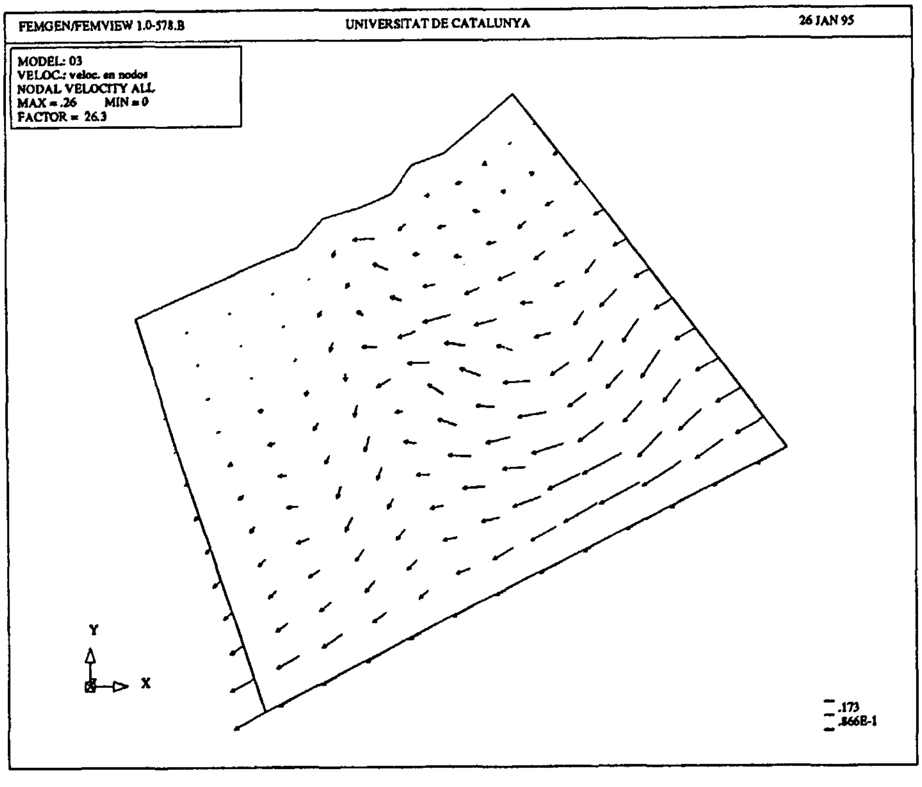



b

Figure 4

*Numerical simulation of the flow in the Blanes canyon area. a) Model solution for the vertically averaged current velocity with bottom friction coefficient* $\gamma_b = 1\ kg/m^3s$. *b) id. with* $\gamma_b = 100\ kg/m^3s$.

## RESULTS

### Water masses distribution

The MECA 93 cruise was performed under early summer conditions. Figure 5a shows that the thermal stratification of the water column was well established during the cruise. The depth of the thermocline (about 40 m) was found to coincide approximately with the locus of the 16 °C isotherm.

The cruise TS diagram is represented in Figure 6. The upper left part of the diagram corresponds to continental shelf water, whose characteristic salinity is under 37.5 psu. Temperature values above 13 °C and salinities between 37.5 and 38.0 psu are associated with surface slope waters. The wedge-type feature observed in the diagram area defined by the 18.0-21.0 °C and 38.0-38.3 psu intervals reveals the existence of subsurface filamentary intrusions (at depths between 20 and 30 m) of slope water across the shelf edge. Such a filament is evident in Figure 5b, which corresponds to the northernmost transect, although similar intrusions have been observed in other transects south of the canyon, as well. Below the 100 m depth layer, three typical water masses are found. According to the terminology proposed by Salat and Cruzado (1981) and Salat and Font (1985), there are "W" or Winter Western Intermediate water (temperature about 12.8 °C, salinity about 38.2 psu), which is formed locally by winter cooling and evaporation; "I" or Levantine Intermediate water (*ca.* 13.5 °C and 38.7 psu) exported from the Eastern Mediterranean basin through the Strait of Sicily; and "D" or Western Mediterranean Deep water (about 13.0 °C and 38.5 psu), which is the result of intense convection processes occurring in the Gulf of Lions during winter. The trace of these three water types in the TS diagrams is a well-known "hook-like" structure.

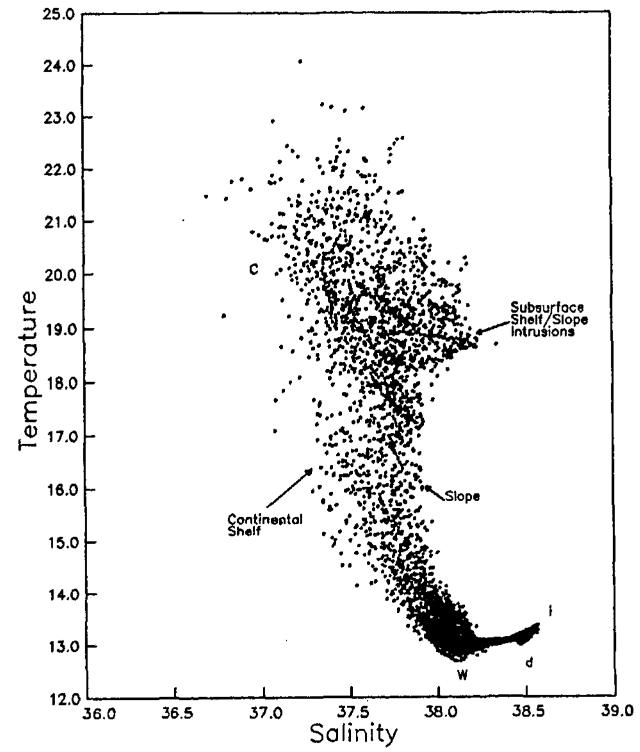



Figure 6

*MECA 93 cruise. Cruise TS diagram with indication of water types. Units are °C and psu.*

In Figures 7a and 7b, the horizontal temperature and salinity distributions at 5 m depth are displayed. The most evident features are two low-salinity nuclei on the slope, one at each side of the Blanes canyon. These surface features are about 1 °C cooler than the neighbouring shelf water. Beneath the mixed layer, the hydrographic structure is simpler (see Fig. 8a and 8b). At 100 m, the trace of the Catalan front – which roughly coincides with the 38.25 psu salinity – is seen to meander and to approximate the coast in the canyon area. The temperature distribution shows a nice temperature maximum within the canyon, which could be produced by upwelling of Levantine Intermediate water linked to a cyclonic circulation pattern.

From the inspection of quasi-contemporary AVHRR images such as that shown in Figure 9, we infer that the origin of the relatively cool surface low-salinity patches was the advection of shelf water from the Gulf of Lions by the Liguro-Provençal-Catalan (or Northern) Current.

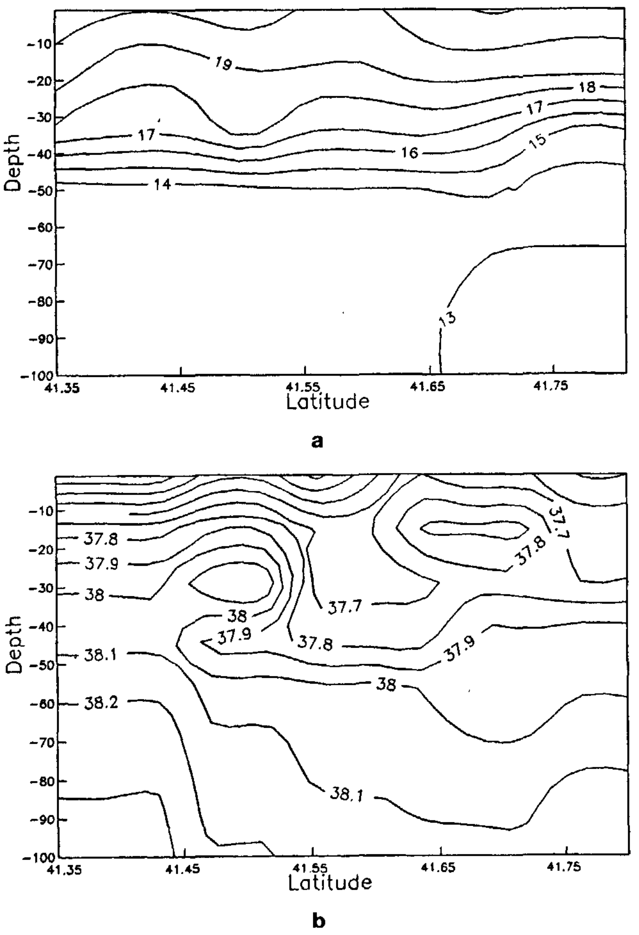



Figure 5

*MECA 93 cruise, transect 1. a) Vertical temperature distribution in the 0-100 m upper layer. Units are °C. b) Vertical salinity distribution in the 0-100 m upper layer. Units are psu. The coast is on the right-hand side. See transect location in Figure 2.*

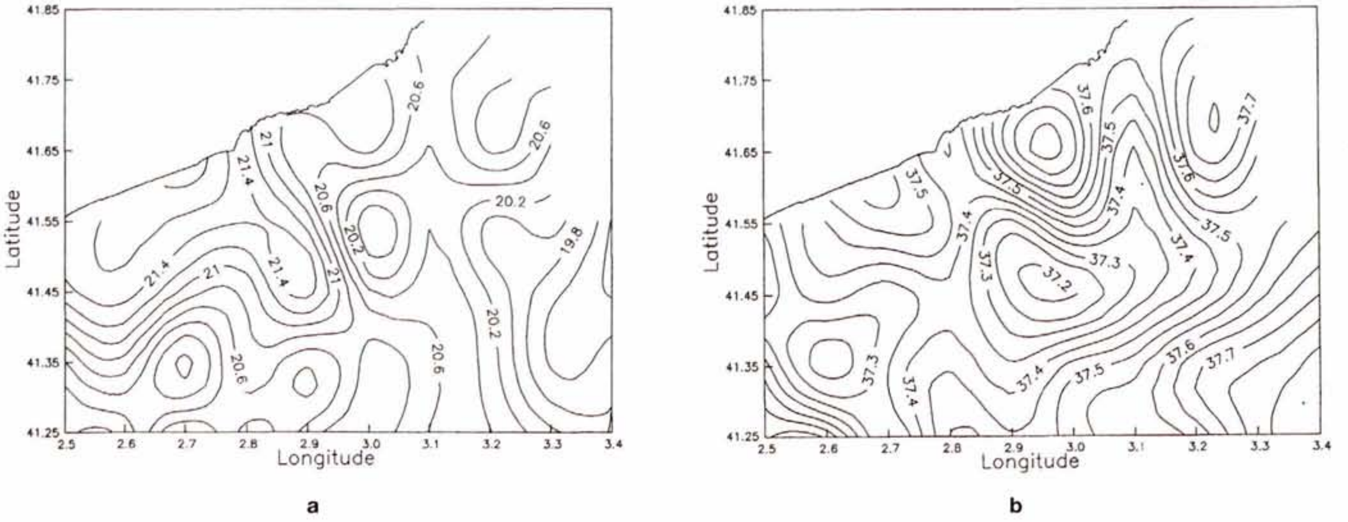



Figure 7

*MECA 93 cruise. Horizontal distributions at 5 m depth. a) Temperature. Units are °C. b) Salinity. Units are psu.*

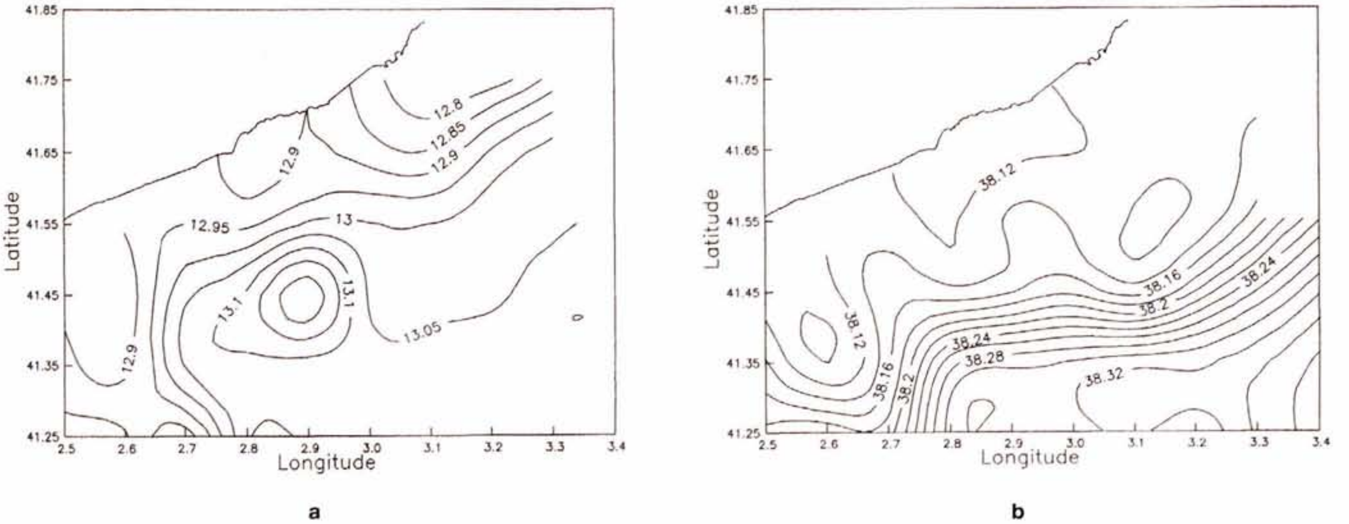



Figure 8

*MECA 93 cruise. Horizontal distributions at 100 m depth. a) Temperature. Units are °C. b) Salinity. Units are psu.*

This process has been described by Le Vourch *et al.* (1992) and other authors. This water is the result of wind-induced cooling plus mixing with the discharge of the Rhône river. The entry of such water bodies into the study area cannot be attributed to a local upwelling feature, since that would inject saltier (denser) and not fresher water into the surface layer. As regards an alternative explanation based on internal mixing processes, we see no forcing mechanisms which would be able to trigger them (the conditions were extremely mild throughout the experiment).

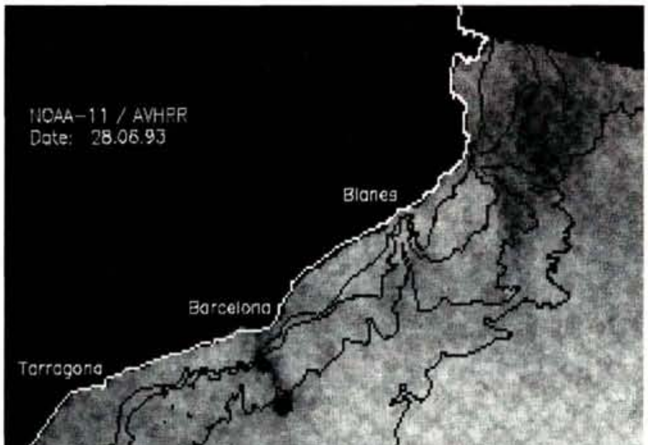



Figure 9

*SST distribution on the Catalan continental shelf and slope from an AVHRR image acquired by NOAA-11 on 28 June, 1993. Darker tones correspond to lower temperatures. Clouds existing south of Barcelona are masked in black.*

### Circulation

Figure 10a shows the mean current velocity distribution corresponding to the 17 m depth layer as derived from on-station 20-minute records acquired with the 150 kHz vessel-mounted ADCP of R/V *Hespérides*, during the MECA 93 cruise. On depths less than 300 m, the displayed current velocities are relative to the bottom. Elsewhere, they are relative to the average speed in the 50-170 m depth layer.

On the slope, the circulation is seen to parallel the isobaths and compares well with the hypothesis worked out on the basis of numerical simulations. Off the shelf break, the flow exhibits negative vorticity both north and south of the Blanes canyon and positive vorticity within the canyon, but the current structure on the shelf is in complete contradiction with the hypothesized flow distribution. The main current direction is NE and it is not clear that the changes in flow direction are linked to the topography.

The trajectories of the LCD floats confirm the described structure of the surface circulation within the study area (see *e.g.* Fig. 11a to 11c). In depths less than 500 m, the LCDs drifted northeastwards, whereas their trajectories were southwestwards off the 500 m isobath. A number of shelf-to-slope and slope-to-shelf transitions of the drifters occurred at several sections across the shelf break. They were probably connected to episodic hydraulic exchanges across the shelf edge but not to particular bathymetric features. All trajectory loops were seen to be anticyclonic. On the other hand, there appears to be a sort of «northern border» which was not crossed by any of the drifters. This could be associated with the cross-shelf front observed in the AVHRR images near the Palamos canyon (see *e.g.* Fig. 9), which according to Le Vourch *et al.* (1992) is probably a seasonal structure.

The wind conditions during the MECA 93 cruise were mild and extremely well suited to SAR monitoring of surface oceanographic features. Visual inspection of the SAR image acquired by ERS-1 on 17 June reveals a number of elongated slicks whose orientation is coherent with the measured surface current distribution (see Fig. 12). The linear brilliant feature observed east of Palamós could be the SAR signature of the above-mentioned cross-shelf front. The sea surface roughness, to which the image intensity is proportional, might be enhanced by flow convergence at the front location. Apart from this, a number of sub-mesoscale cyclonic vortexes some 5 km in diameter can be identified southwest of the Blanes and Palamós canyon heads (see image enlargements in Figures 13a and 13b). These are located close to the coast and were missed by the mesoscale sampling performed during MECA 93. A much bigger cyclonic eddy, with a diameter of *ca.* 20 km occupies the Gulf of Roses north of the study area (see Fig. 13c) and probably results from the interaction between the northward-flowing shelf circulation and the coastal geometry. As for the microscale eddies, their dynamics is not clear to us.

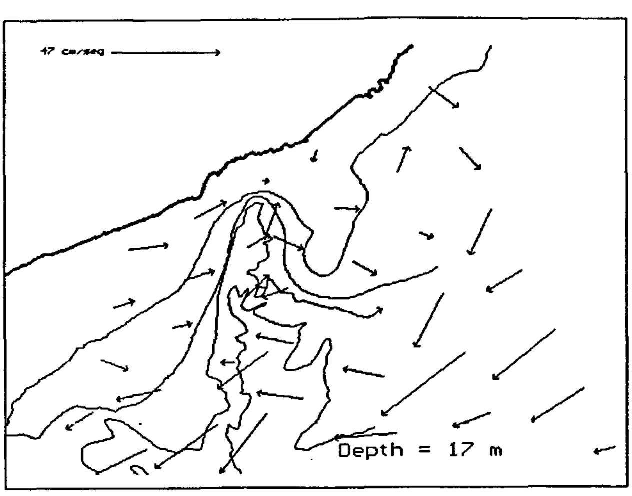
The ADCP currents computed at depths below 50 m suggest that the circulation below the thermocline was southwestwards, as on the continental slope (see Fig. 10b).

## DISCUSSION

### The surface current reversal

The inversion of the surface current direction in the Blanes canyon area is the most notable findings of the MECA 93 experiment. Sabatés and Masó (1992) stated that such an event occurred in May 1983 and that it was due to the formation of a strong inverted density front. They reported that this current reversal produced an unsual distribution of larval fishes on the shelf and slope domains.

In our opinion, two facts were responsible for the observed circulation pattern during MECA 93: dynamic «decoupling» of the upper layer from the rest of the water column; and advection of relatively light surface water on to the slope. It is well known that thermal stratification hampers the vertical diffusion of momentum.



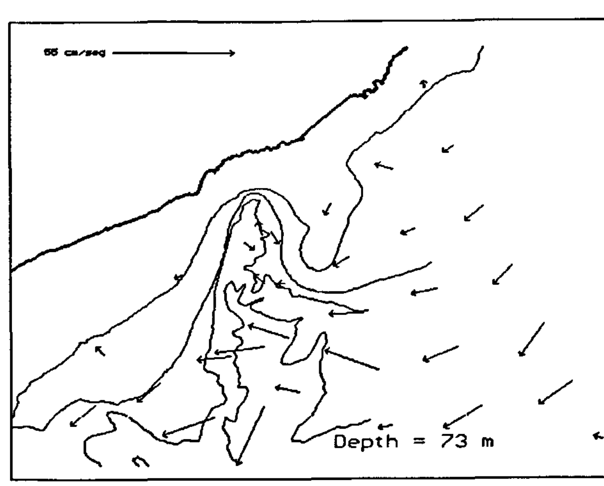




Figure 10

*MECA 93 cruise. ADCP mean current velocity distributions. a) 17 m depth. b) 73 m depth. The 100, 200, 400 and 1000 m isobaths are depicted.*

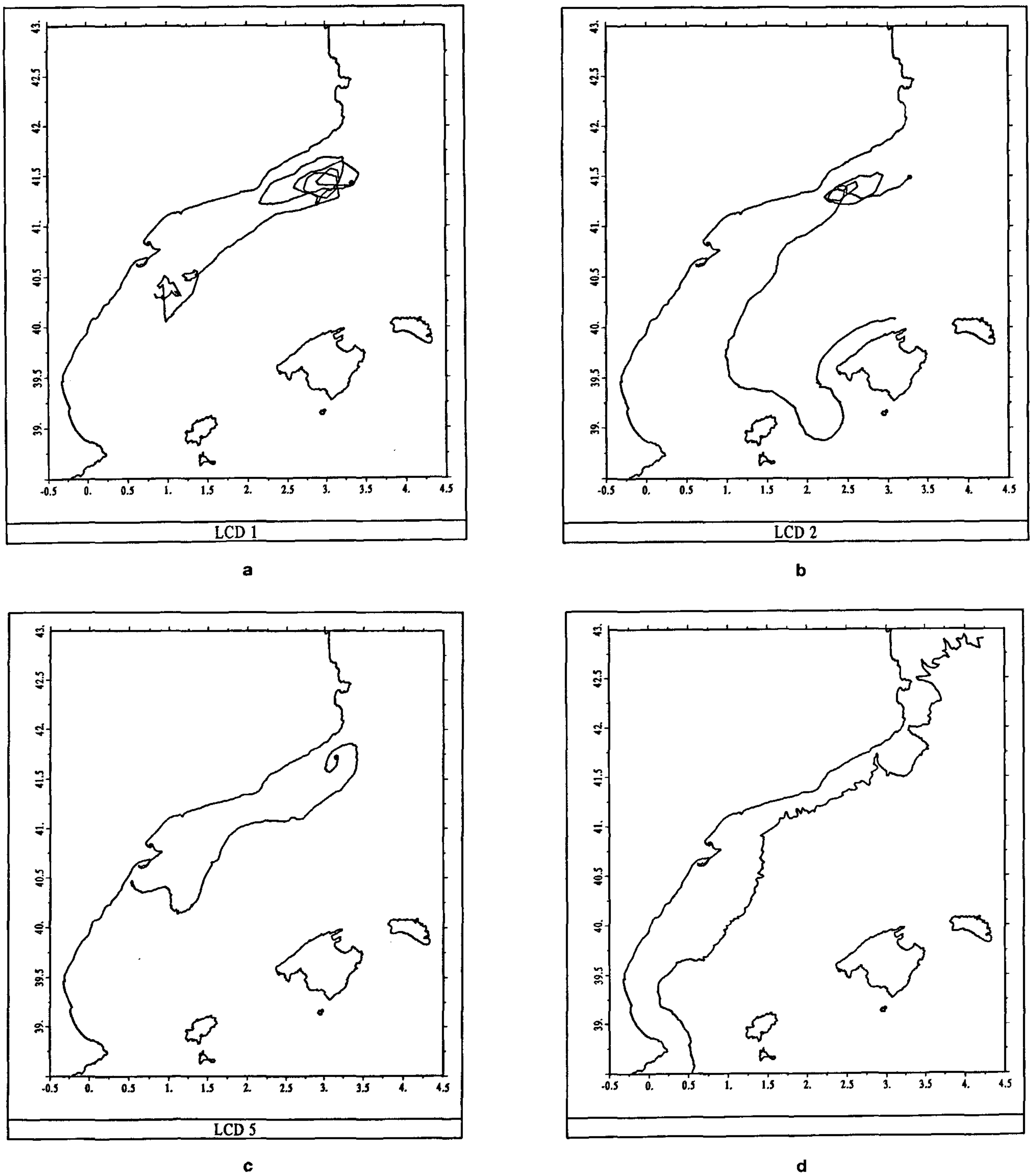



Figure 11

*MECA 93 cruise. LCD trajectories off the Catalan coast. a) LCD 1. b) LCD 2. c) LCD 5. d) Locus of the 500 m bottom depth. The small circles indicate the points where the floats were released.*

Under mild or no wind conditions, the dynamics of the surface layer above the thermocline is approximately geostrophic. In this situation, the presence of light water on the slope inducing an offshore horizontal pressure gradient could result in a northeastward surface flow on the shelf. The geostrophic computations at 5 dbar relative to the 50 dbar level which are shown in Figure 14 are coherent with this explanation. It can be noted that the surface geostrophic flow distribution is almost identical, even in detail, to the structure of the surface current field computed from ADCP measurements.

The thermal stratification of the water column produces two "decoupled" layers whose potential vorticity must be conserved independently. This does not mean, however, that the topographic steering effects do not influen-

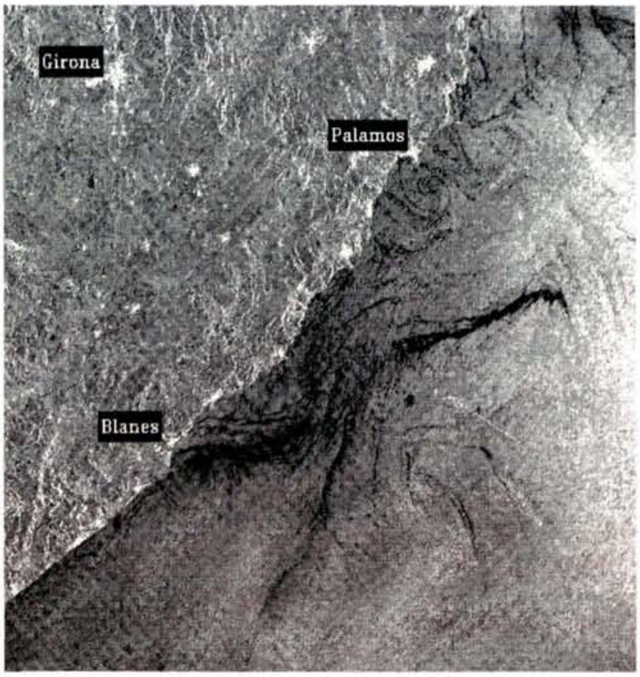



Figure 12

*SAR image of the study area acquired by ERS-1 on 17 June, 1993. The offshore position occupied by R/V* Hespérides *- which was steaming towards the northeast at that moment - can be easily identified (arrow).*

ce the upper layer dynamics at all. According to Hide (1971), there may still be some topographic steering of the surface flow in such a stratified fluid system. Only if the current speed tends to zero, is the steering completely lost.

## The extension of the surface current reversal

During the MECA 93 cruise we observed a surface current reversal similar to that described by Sabatés and Masó in May 1983. From the surface temperature and salinity distributions published by Masó and Tintoré (1991), we assume that no such inversion ocurred during May/June 1984. We hypothesize that this process could be a seasonal but interannually varying phenomenon. Further research on this issue based on remote-sensing data is in progress.

According to the extent of the plume of cool surface slope-water observed in the AVHRR images (see *e.g.* Fig. 9) and to the paths of the LCD buoys (see Fig. 11), it seems clear that the surface flow reversal which occurred in June 1993 was not restricted to the Blanes canyon area but affected a much larger stretch of the Catalan continental shelf. On the other hand, the sequence of

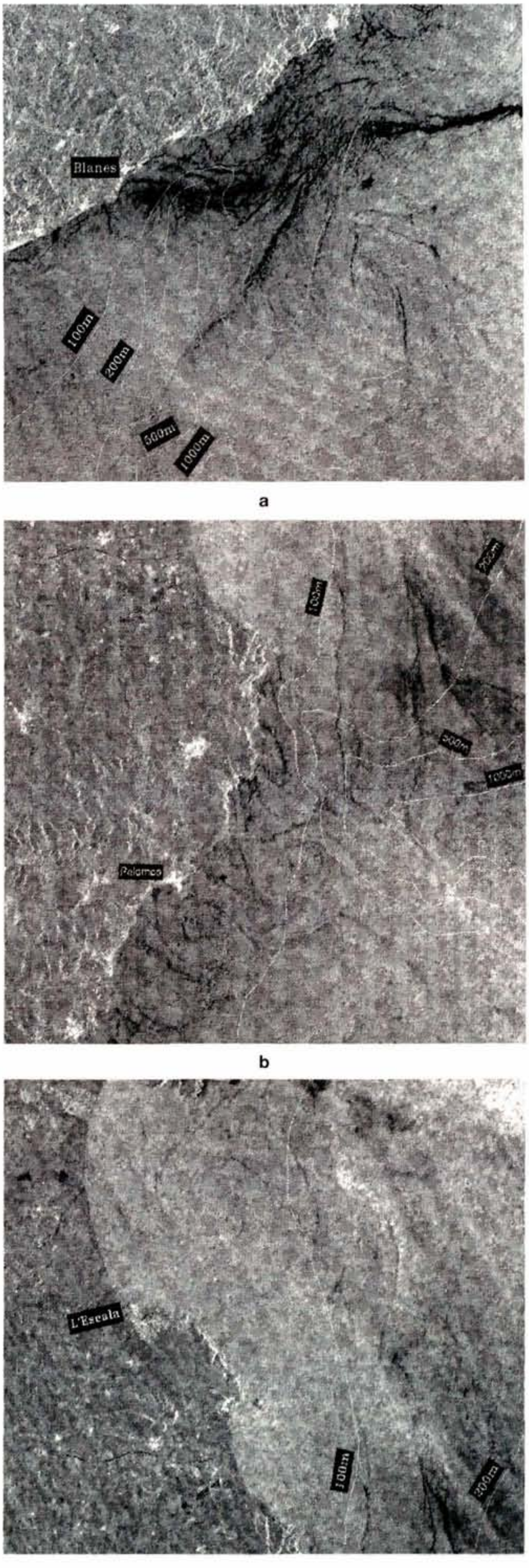



Figure 13 ►

*Subscenes of the SAR image acquired on 17 June, 1993. a) Blanes canyon. b) Palamós canyon. c) Gulf of Roses.*

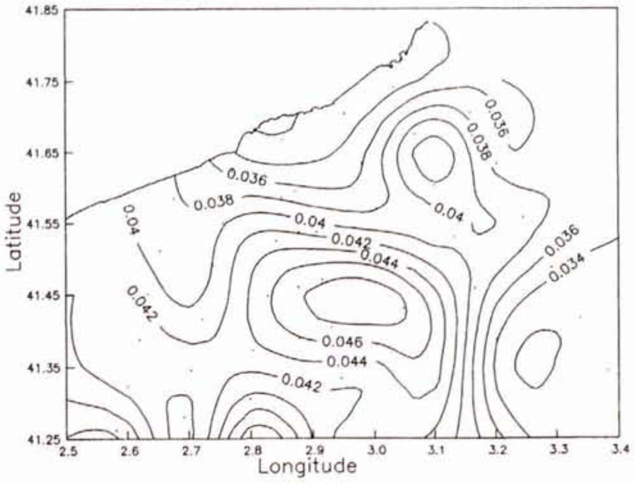



Figure 14

*MECA 93 cruise. Dynamic heights at 5 dbar relative to the 50 dbar level. Units are dyn m.*

SST distributions shown in Figure 15 suggests that the surface current on the shelf was probably again to the southwest by the end of July.

## CONCLUSIONS

The MECA 93 oceanographic cruise was carried out in the Blanes canyon region in June 1993. CTD and ADCP measurements were conducted throughout the survey, as well as LCD tracking. Contemporary NOAA/AVHRR and ERS-1/SAR imagery was available for the purposes of the experiment.

Summer stratification conditions were found during the cruise. The thermocline was located at 40 m depth. The cruise TS diagrams reveal intrusions of slope-water filaments across the shelf edge. The surface distributions of temperature and salinity show patches of cool and low-salinity water on the slope advected by the Liguro-Provençal-Catalan or Northern Current from the Gulf of Lions.

Contrary to what we expected, the surface flow direction was to the northeast on the shelf and no clear control of the bottom topography was evident on the shelf circulation. ADCP measurements at depths below 50 m suggest that the prevailing flow pattern on the shelf was to the southwest below the thermocline. The flow on the slope was observed to be SW at all levels.

We hypothesize that the dynamics of the mixed layer above the thermocline was essentially geostrophic and that it was decoupled from the rest of the water column. In this situation, the flow of relatively cold and low-salinity water on to the slope was responsible for the inversion of the horizontal pressure gradient and the resulting surface current reversal on the shelf. This current reversal process was not restricted to the Blanes canyon area and might be a seasonal but interannually varying phenomenon.

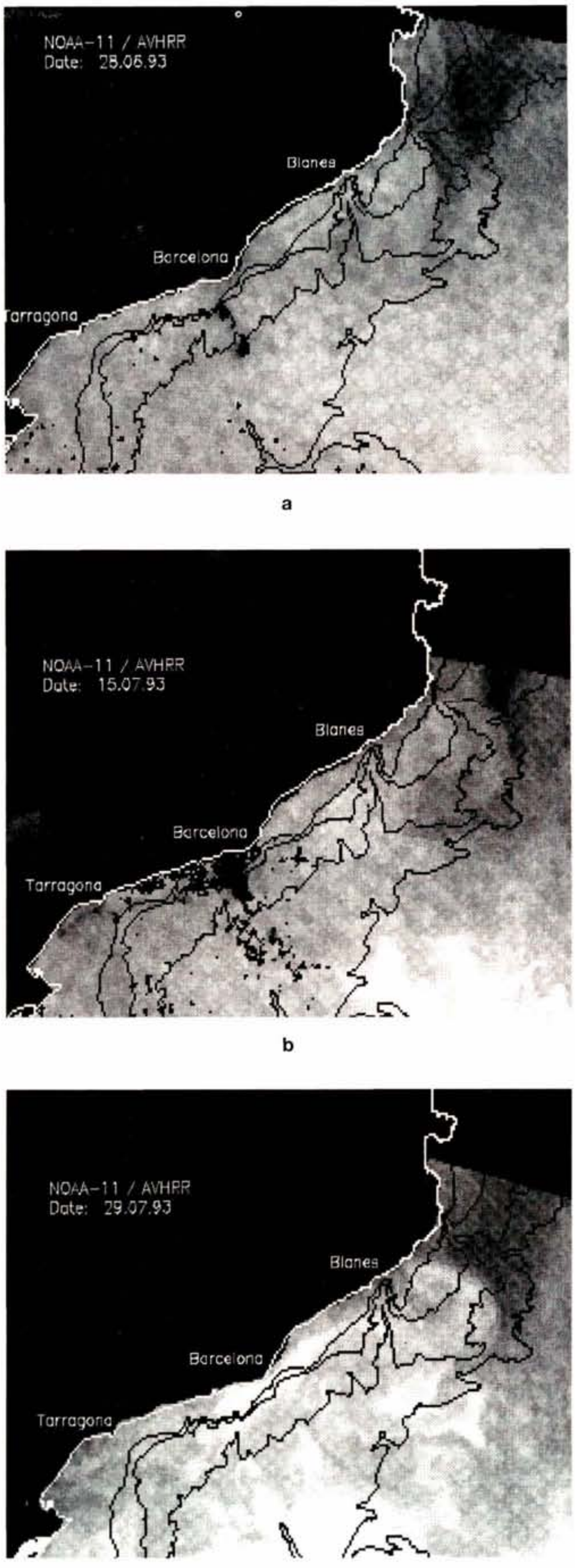



Figure 15

*Sequence of SST distributions in the NW Mediterranean. a) 28 June 1993. b) 15 July 1993. c) 29 July 1993. Darker tones correspond to lower temperatures. Clouds are masked in black.*

## Acknowledgements

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